APPENDIX A

Analysis and Simulation of the Protocol

A. Performance Analysis

A mathematical equation can be derived for the throughput of the system using a renewal theory. Since the behavior of the protocol is very similar to non-persistent CSMA/CD a similar analysis is used, the following assumptions about the message arrival process and message length distribution are made. The message arrival process is assumed to be Poisson with parameter G, where G is the normalized load in packet arrivals per slot. The length of the message is assumed to be geometric with parameter g_d. *i.e*

$$P(S=k)=\begin{cases} g_d(1-g_d)^{k-1} & k=1,2,3... \\ 0 & otherwise \end{cases}$$

It is assumed that the system is slotted. The size of the slot as described above equals an IDI. A transmission attempt is vulnerable to collision for the same duration of time. An unsuccessful transmission lasts a receiver detection interval (RDI). Let RDI be an integral number of slots (R). The mean successful packet transmission time (S) is $1/g_d$ slots. The offered load to the channel is G. The mean duration of a successful transmission and unsuccessful transmission is $S + 1$ and $R + 1$ slots respectively. The number of idle slots (I) is given by the distribution,

$$P(I=k)=\left(1-e^{-G}\right)\left(e^{-G}\right)^{k-1} \quad k=1,2,3...$$

and the expected number of idle slots is

$$E(I)=\frac{1}{1-e^{-e}}$$

The probability of a single transmission in a given slot given that a transmission attempt was made is given by,

$$P_{succ}=\frac{Ge^{-G}}{1-e^{-G}}$$

The channel is always either in a busy state or idle state. A given busy period may contain n transmission attempts of which l are successful. This probability is given by,

$$P\{B=l(S+1)+(n-l)(R+1)\}=$$
$$e^{-G}\left(1-e^{-G}\right)^{n-1}\binom{n}{l}P_{succ}^{l}\left(1-P_{succ}\right)^{n-1}$$

Therefore, the mean busy duration is given by,

$$E(B) = \sum_{n=1}^{\infty}\sum_{l=0}^{n}(l(s+1)+(n-l)(R+1))$$
$$P\{B = l(S+1)+(n-l)(R+1)\}$$
$$= P_{succ}(S+1)+(1-P_{succ})(R+1)$$

Of the busy period only the l transmissions result in a valid data transfer. The probability that there are l useful transmissions in a busy period is given by,

$$P(U-l) = \sum_{n-l}^{\infty} P\{B = l(S+1)+(n-l)(R+1)\}$$

and the average useful period is given by,

$$E(U) = \sum_{n-l}^{\infty} lSP(U=l) = \frac{SP_{succ}}{e^{-G}}$$

and therefore the throughput (n) is given by,

$$n = \frac{E(U)}{E(B)+E(I)} = \frac{SGe^{-G}}{SGe^{-G}+(1-Ge^{-G}-e^{-G})R+1}$$

B. Protocol Simulation Implementation

The protocol was implemented in *C* as a discrete time simulation. It is assumed that the system is a fully connected mesh of N nodes. This implies that every node is within the radio range of every other node. Note that these simulations do not show the significant improvement that is achieved by the WCD protocol by enabling multiple simultaneous non-interfering transmissions in a multihop network. The node model is comprised of a traffic generator and a MAC layer service.

B.1 Assumptions

In the MAC service model some physical layer constraints were considered. It is assumed that a node takes a finite time to switch from transmit mode to receive mode. This time period is called the switching interval. The effect of these switching times on the performance of the protocol has been studied. For a transmission to be successful, participation of both the source and destination node is necessary. If both the SN and DN are in transmit mode, because of half duplex operation of the data channel, the destination cannot assert the feedback channel. It is assumed that the physical channel is slotted and all nodes are synchronized. The channel is considered to be error free and the effects of fading are not considered. The traffic generator packet arrival process is Poisson (i.e., exponential inter arrival times). The message length

distribution is geometric with a default mean message size of 192 bytes ($S = 12$) which is representative of the mean packet size in a typical LAN environment. However, the effect of packet size on the performance of the protocol is studied. The packet transmission attempts occur at the beginning of a slot.

B.2 Choice of IDI and RDI parameters

Each slot needs to be long enough for a carrier to be detected and the feedback channel to be asserted. The radius of the network is 50m which corresponds to a round trip time of 0.35μs. At 100 Mbps data rate this corresponds to 35bits. If we assume similar times for carrier detection and tone assertion this slot should be at least 1.1μs. We chose the closest power of 2 in bytes for the slot size which is also the IDI. This gives an IDI of 16 bytes. The time to detect a collision is an integral number of slots (R). Based on the IEEE 802.11 physical layer and MAC layer headers add up to 240 bits. Again choosing the closest power of two, RDI is 32 bytes. Note that the choice of IDI used in the simulations is conservative. The smaller the IDI, the better is the performance of WCD over other protocols. The time to detect a transmission in the IEEE 802.11 standard is 16 symbols. If it takes about the same time to assert the feedback signal, the idle slot can be made 8 bytes or even 4 bytes in networks with smaller round trip time. A summary of the simulation parameters is shown in Table.I.

Parameter	Value
Max radius of the network	50m
Round Trip delay	0.35μs
Data Ratae	100 Mbps
Number of nodes	$\in\{5,8,16,32\}$
Slot	16 bytes
Channel	Error free
Simulation Length	10000000 slots
Statistics Start	50000 Slots
Mean Message Length	192 bytes
Message Arrival Process	Poisson
Message Size Distribution	Geometric
Switching Time	$\in\{0,1\}$ slots
Backoff Range	$\in\{5,10,20\}$ slots

Table 1

C. Description of the results

Using the simulation parameters of S and R of 12 and 2 respectively in the throughput equation, we get a maximum throughput of 0.7612 is obtained. This matches very closely the maximum throughput obtained from simulation (0.767). The comparison of analysis and simulation for different mean packet sizes is given in table II.

Packet Size	Simulation	Analysis
1536 bits	0.767	0.7612
2560 bits	0.845	0.8416
4-96 bits	0.896	0.8948
8000 bits	0.940	0.9428
19080 bits	0.973	0.9754

Table II

The improvement of WCD over RI-BTMA is shown in FIG. A. The throughput of RI-BTMA was calculated using the equation in [15] and choosing the slot size as R. The mean message length then becomes S/R. It can be seen that as the time difference between detecting the carrier and detecting a collision increases, the improvement from WCD becomes more significant.

The WCD protocol does not have an adaptive mechanism to adjust the backoff range according to load. For a network of 5 nodes and an RDI of 2 slots the optimum backoff range is 10. Each transmission attempt lasts at least 2 slots. If 5 nodes are active in the network the optimum probability of access is 0.2. FIG. B shows increasing or decreasing the backoff range from the value 10 decreases the maximum throughout that is achieved. When the network is lightly loaded the probability of collision is small and so a smaller backoff range parameter provides faster access to the medium. For similar reasons at higher loads a bigger backoff range is better. Making the range too large results in underutilization of the capacity. These conclusions are supported by FIG. B where the delay performance of the protocol is plotted against the offered load for different backoff ranges. Simulation with backoff range of 11 and 9 give maximum throughput of 0.765 which is very close to the optimal throughput. The performance with optimal backoff range of 10 gives better delay and throughput performance. The performance is not optimal at low loads when the number of contending nodes is small. An adaptive protocol which estimates the number of contending users and dynamically adjusts the backoff range will enhance the protocol performance. Note that the optimum backoff range needs to be based on the number of users actively contending who will potentially interfere with the reception at the destination. The time that a node takes to switch between transmit and receive mode affects the efficiency of the protocol. If a node takes a long time to switch (say T) to transmit mode, the node has to transition to transmit state at least T secs before the actual transmission attempt. A node in the transmit mode cannot listen to the data channel. Therefore this node cannot respond to any packet for which it is the destination. This results in a loss of throughput. This performance loss with a switching interval of one slot is shown in FIG. C. This performance loss decreases when there are a larger number of nodes in the network or if a larger backoff range is used. These mechanisms decrease the probability of a source-destination pair being in transmit mode at the same time.

For a small number of active nodes, the protocol performs slightly better because the probability of collision is smaller. FIG. D compares the delay performance as a function of the number of nodes in the network. In each simulation run, the corresponding optimum backoff

range is chosen. Hence at low loads the mean access delay is larger with a larger number of nodes.

C.1 Comparison with Current Wireless Standards

Table III compares the performance of the proposed protocol with the current wireless standards at the data rates each has been proposed for and at 100Mbps. The throughput of DFWMAC and HIPERLAN is obtained by using the throughput equations derived in [3] and [1] respectively. For scaling the performance to higher data rates we have assumed that the turn-around times are constant. WCD outperforms both the protocols and provides a significant improvement even at the rates at which the standards have been proposed.

Protocol Rate (Mbps)	WCD 2/24/100	DFWMAC 100	DWFMAC 2	Hiperlan 100	Hiperlan 24
1536 bits	0.77	0.03	0.48	0.09	0.26
2560 bits	0.85	0.06	0.58	0.13	.035
4096 bits	0.90	0.09	0.65	0.19	0.45
8000 bits	0.94	0.17	0.73	0.31	0.57
19080 bits	0.97	0.33	0.79	0.48	0.69

Table III